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**ELECTRON DENSITY MEASUREMENT AND PLASMA PROCESS  
CONTROL SYSTEM USING CHANGES IN THE RESONANT FREQUENCY  
OF AN OPEN RESONATOR CONTAINING THE PLASMA**

**CROSS-REFERENCE TO RELATED APPLICATIONS**

The present application is related to co-pending applications entitled "ELECTRON DENSITY MEASUREMENT AND PLASMA PROCESS CONTROL SYSTEM USING A MICROWAVE OSCILLATOR LOCKED TO AN OPEN RESONATOR CONTAINING THE PLASMA," attorney docket number 2312-0711-2YA PROV and "ELECTRON DENSITY MEASUREMENT AND PLASMA PROCESS CONTROL SYSTEM USING A MICROWAVE OSCILLATOR LOCKED TO AN OPEN RESONATOR CONTAINING THE PLASMA," attorney docket number 2312-0709-2YA PROV, both of which have been filed concurrently herewith. Both of those applications are herein incorporated by reference in their entirety.

**BACKGROUND OF THE INVENTION**

**Field of the Invention**

The present invention provides a method and system for measuring and controlling electron densities in a plasma processing system, such as is used in semiconductor processing systems.

**Description of the Background**

Known microwave-based techniques for determining plasma electron densities include: (1) microwave interferometry, (2) measurement of reflection and absorption, and (3) perturbation of cavity resonant frequencies. Microwave interferometry involves the determination of the phase difference between two microwave beams. The first beam provides a reference signal, and the second beam passes through a reactive environment and undergoes a phase shift relative to the first beam. The index of refraction is calculated from the measured change in the phase difference between the two beams. The interferometric technique has

been document by Professor L. Goldstein of the University of Illinois at Urbana. Interferometry is described in the following U.S. Patents: 2,971,153; 3,265,967; 3,388,327; 3,416,077; 3,439,266; 3,474,336; 3,490,037; 3,509,452; and 3,956,695, each of which is incorporated herein by reference. Examples of other non-patent literature describing interferometry techniques include: (1) "A Microwave Interferometer for Density Measurement Stabilization in Process Plasmas," by Pearson et al., Materials Research Society Symposium Proceedings, Vol. 117 (Eds. Hays et al.), 1988, pgs. 311-317, and (2) "1-millimeter wave interferometer for the measurement of line integral electron density on TFTR," by Efthimion et al., Rev. Sci. Instrum. 56 (5), May 1985, pgs. 908-910. Some plasma properties may be indirectly determined from measurements of the absorption of a microwave beam as it traverses a region in which a plasma is present. Signal reflections in plasmas are described in U.S. Patent numbers 3,599,089 and 3,383,509.

Plasma electron densities have also been measured using a technique which measures the perturbations of cavity resonant frequencies. The presence of a plasma within a resonator affects the frequency of each resonant mode because the plasma has an effective dielectric constant that depends on plasma electron density. This technique has been documented by Professor S.C. Brown of the Massachusetts Institute of Technology. Portions of this technique are described in U.S. Patent number 3,952,246 and in the following non-patent articles: (1) Haverlag, M., et al., J. Appl Phys 70 (7) 3472-80 (1991): Measurements of negative ion densities in 13.56 MHZ RF plasma of  $CF_4$ ,  $C_2F_6$ ,  $CHF_3$ , and  $C_3F_8$  using microwave resonance and the photodetachment effect; and (2) Haverlag, M., et al., Materials Science Forum, vol. 140-142, 235-54 (1993): Negatively charged particles in fluorocarbon RF etch plasma: Density measurements using microwave resonance and the photodetachment effect.

#### SUMMARY OF THE INVENTION

It is an object of the present invention to provide a more accurate plasma measuring system than the prior art.

It is a further object of the present invention to provide an improved plasma measuring system using plasma induced changes in the frequencies of an open resonator.

These and other objects of the present invention are achieved using a voltage-controlled programmable frequency source that sequentially excites a number of the resonant modes of an open resonator placed within the plasma processing apparatus. The resonant frequencies of the resonant modes depend on the plasma electron density in the space between the reflectors of the open resonator. The apparatus automatically determines the increase in the resonant frequency of an arbitrarily chosen resonant mode of the open resonator due to the introduction of a plasma and compares that measured frequency to data previously entered. The comparison is by any one of (1) dedicated circuitry, (2) a digital signal processor, and (3) a specially programmed general purpose computer. The comparator calculates a control signal which is used to modify the power output of the plasma generator as necessary to achieve the desired plasma electron density.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

A more complete appreciation of the invention and many of the attendant advantages thereof will become readily apparent with reference to the following detailed description, particularly when considered in conjunction with the accompanying drawings, in which:

Figure 1 is a schematic illustration of a computer system for implementing the measurement and control of the present invention;

Figure 2 is a graph of the sequential excitation of the modes of an open resonator by the sweep of the frequency of the programmable frequency source while the resonant frequencies of the modes are being shifted due to the formation of the plasma;

Figure 3 is a block diagram of a circuit for measuring and controlling plasma electron density according to the present invention;

Figure 4 is a graph that is similar to Figure 2, but without the presence of the plasma shifting the resonances to higher frequencies;

Figures 5A and 5B are graphs that illustrate the problems with a non-monotonic change in the plasma electron density; and

Figure 6 is a graph of the sequential excitation of the modes of an open resonator by sweeping the frequency of the programmable frequency source a number of times in series while the resonant frequencies of the modes are being shifted due to the formation of the plasma.

#### **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, Figure 1 is a schematic illustration of an embodiment of a measurement and control system, according to the present invention, for a plasma processing system. In this embodiment, a computer 100 implements the method of the present invention, wherein the computer housing 102 houses a motherboard 104 which contains a CPU 106, memory 108 (e.g., DRAM, ROM, EPROM, EEPROM, SRAM and Flash RAM), and other optional special purpose logic devices (e.g., ASICs) or configurable logic devices (e.g., GAL and reprogrammable FPGA). The computer 100 also includes plural input devices, (e.g., a keyboard 122 and mouse 124), and a display card 110 for controlling monitor 120. In addition, the computer system 100 further includes a floppy disk drive 114; other removable media devices (e.g., compact disc 119, tape, and removable magneto-optical media (not shown)); and a hard disk 112, or other fixed, high density media drives, connected using an appropriate device bus (e.g., a SCSI bus, an Enhanced IDE bus, or an Ultra DMA bus). Also connected to the same device bus or another device bus, the computer 100 may additionally include a compact disc reader 118, a compact disc reader/writer unit (not shown) or a compact disc jukebox (not shown). Although compact disc 119 is shown in a CD caddy, the compact disc 119 can be inserted directly into CD-ROM drives which do not require caddies. In addition, a printer (not shown) also provides printed listings of frequency graphs showing resonant frequencies of the open resonator.

As stated above, the system includes at least one computer readable medium. Examples of computer readable media are compact discs 119, hard disks

112, floppy disks, tape, magneto-optical disks, PROMs (EPROM, EEPROM, Flash EPROM), DRAM, SRAM, SDRAM, etc. Stored on any one or on a combination of computer readable media, the present invention includes software for controlling both the hardware of the computer 100 and for enabling the computer 100 to interact with a human user. Such software may include, but is not limited to, device drivers, operating systems and user applications, such as development tools. Such computer readable media further include the computer program product of the present invention for controlling a plasma processing system. The computer code devices of the present invention can be any interpreted or executable code mechanism, including but not limited to scripts, interpreters, dynamic link libraries, Java classes, and complete executable programs.

In an alternate embodiment, the computer 100 includes a digital signal processor (not shown) for performing signal processing on received inputs. In yet another alternate embodiment, the CPU 106 is programmed with software to perform digital signal processing routines analogous to the internal operation of a DSP. In a further embodiment, the computer 100 is replaced by a DSP and memory (e.g., on a printed circuit board) for performing the operations of the computer described herein. Likewise, the functions of the DSP may be replaced by dedicated analog and/or digital circuitry for performing the operations described herein.

As shown in Figure 3, the computer 100 is programmed to measure a plasma electron density and control a programmable frequency source (PFS) 201. One embodiment of a programmable frequency source includes a D/A converter coupled to a voltage-controlled frequency modulated microwave oscillator. However, the frequencies applied by the programmable frequency source 201 depend on the behavior of the resonant frequencies of the open resonator modes as the plasma is established by the plasma generator 320. For purposes of the description of Figure 2, it is assumed that the plasma electron density increases monotonically from its initial value to its final value (e.g.,  $2 \times 10^{12} \text{ cm}^{-3}$ ). As a non-limiting example, it is also assumed that the mode spacing in the empty (i.e., evacuated) resonator 305 is approximately  $c/2d = 500 \text{ MHz}$ , where  $c$  is the speed of light in vacuum and  $d$  is the reflector spacing, i.e., the spacing between the reflectors. As shown in Figure 2, the

mode spacing with the plasma present is  $c/(2nd)$ , where  $n$  is the index of refraction. If the index of refraction is not uniform as a function of position,  $n$  may be replaced by  $\langle n \rangle$ , its mean value along an appropriate path between the reflectors. The spacing is not quite uniform because the index of refraction depends very slightly on the frequency as well as on the plasma electron density and spurious sources of phase shift associated with the coupling apertures.

To control the plasma processing system, the system determines a final operating frequency at which the system is to operate to establish and maintain a desired plasma electron density. The final operating frequency is determined as follows. At the time  $T_0$ , just as the plasma begins to form, the computer 100 sets the frequency of the programmable frequency source 201 to a predetermined maximum frequency,  $f_{\max}$  (e.g., 38.75 GHz). The computer 100 then decreases the frequency with respect to time (e.g., by changing a digital control signal output by the computer 100). In the illustrated embodiment, the decrease is linear, but in practice, the decrease can be either linear or non-linear, but in either case, it should be repeatable and thus predictable. The frequency of the programmable frequency source 201 is decreased until it reaches a minimum frequency,  $f_{\min}$ , (e.g., 36.75 GHz) at the time  $T_1$ , which is just after the plasma has essentially attained its steady-state density  $2 \times 10^{12} \text{ cm}^{-3}$ . The selection of the frequencies  $f_{\max}$  and  $f_{\min}$  are somewhat arbitrary. They are chosen in the microwave spectrum and about a nominal frequency convenient for microwave apparatus, i.e., ~35GHz. If the maximum frequency has been arbitrarily chosen to be 38.75 GHz, then choosing  $f_{\min}$  to be 36.75 GHz is such that eight resonant modes are observed over the frequency range  $f_{\min} < f < f_{\max}$  in the resonant cavity without a plasma. The minimum number of modes scanned is determined by (1) the method of sweeping the frequency (with linear or non-linear changes) with time and (2) the time over which the frequency is swept. Furthermore, the microwave apparatus can have a range within which it may be varied (limited by hardware constraints). The time over which the frequency is swept should be greater than the plasma adjustment period (formation time  $T_1 - T_0$ ) to give meaningful results. The sweep time scale includes the decreasing and increasing sweeps. In a first embodiment, it is assumed that the plasma electron

density between times  $T_0$  and  $T_1$  is monotonically increasing so that number of modes passed while increasing or decreasing the sweeping frequency is counted properly.

Generally, the resonances are indicated by a greatly enhanced value of the transmitted microwave energy and are counted as the frequency of the programmable frequency source 201 is decreased over the defined range. Likewise, when increasing the frequency from the programmable frequency source 201 over the defined range, the modes are counted and correlated with the modes counted during the decrease. During the decrease in frequency, the system detects the appearance of resonant frequencies in the open resonator and records the frequencies of the oscillator which produced the resonant frequencies. Figure 2 is a graph of the sequential excitation of the modes of an open resonator by the sweep of the frequency of the programmable frequency source while the resonant frequencies of the modes are being shifted due to the formation of the plasma. In the example of Figure 2, eight resonances of the open resonator are excited as the frequency of the programmable frequency source 201 decreases from its maximum frequency,  $f_{max}$ , to its minimum frequency,  $f_{min}$ .

Having decreased the programmable frequency source 201 to its minimum frequency, the system then increases the frequency of the programmable frequency source 201 with respect to time until, at the time  $T_2$ , the frequency again reaches the maximum frequency,  $f_{max}$ . As during the decrease, resonant frequencies are detected and recorded, and the increase may either be linear, as shown in Figure 2, or non-linear with respect to time. The time between  $T_1$  and  $T_2$  is called the retrace time. During the retrace time of Figure 2, four resonant frequencies of the open resonator are excited. The system determines the difference between the number of resonant frequencies during the decrease and the increase. This difference is the integer part of a characteristic called the fringe order. In the example of Figure 2, the difference is four.

The fractional part of the fringe order is obtained in part from the difference between (a) the frequency,  $f_{final}$ , of the final resonant frequency excited (e.g.,  $f_{final} = 38.644$  GHz in Figure 2) and (b) the highest resonant frequency of the empty open

resonator that is also less than  $f_{final}$ . In this case, that frequency,  $f_{open}$ , is 38.500 GHz, and is determined by performing a calibration run apriori to determine the mode spacing and the frequencies of the resonant modes. Calibration is done when no plasma is present within the chamber. This is an accurate measurement and check of the mode spacing given by  $c/2d$  and the resonant frequencies present when there exists no plasma (i.e.,  $f(q) = (c/2d)(q+1/2)$ ). The difference is divided by the mode spacing of the empty open resonator (e.g., 0.5 GHz). Thus, the fractional part of the fringe order is given by:

$$\frac{f_{final} - f_{open}}{\text{mode spacing}} = \frac{38.644 - 38.5}{0.5} = 0.288$$

The entire fringe order is then 4.288, and the frequency shift of the mode is  $4.288 \times (\text{mode spacing}) = 4.288 \times 0.500 \text{ GHz} = 2.144 \text{ GHz}$ .

Just as the system calculates the open resonant frequency,  $f_{open}$ , below the final frequency,  $f_{final}$ , the system also determines the open resonator frequency,  $f_{omin}$ , just below the minimum frequency,  $f_{min}$ . The value of the index of refraction in the steady-state condition is then calculated according to:

$$\frac{f_{omin}}{f_{final}} = \frac{36.5}{38.644} = 0.945.$$

A more concrete example is explained hereafter with reference to Fig. 2. Starting from a point on the mode characteristic for which the resonant frequency is 38.644 GHz (near the right side of Fig. 2) an imaginary line is drawn down to the dashed horizontal line at 38.500 GHz. This drop corresponds to a frequency change of 0.144 GHz. Then, when moving to the left to the axis of ordinates along the 38.500 GHz line, there is a drop of four mode spaces of the empty open resonator; i.e.,  $4 \times 0.500 \text{ GHz} = 2.000 \text{ GHz}$ , to reach 36.500 GHz. Note that 36.500 GHz is the starting resonant frequency of the mode characteristic that ends with a resonant frequency of 38.644 GHz. It should be noted that a one-to-one correspondence exists between the frequency vs. time plot of Figure 2 and a plot of the voltage controlling the programmable frequency source 201 vs. time. Thus, it is quite



reasonable to interpolate between the several curves in the manner described herein.

In an alternate embodiment, if the plasma electron density does not increase monotonically during the period when the plasma forms, the procedure described above is modified. The decrease in the frequency of the programmable frequency source 201 during the time period between  $T_0$  and  $T_1$  must be controlled in such a way that no mode of the open resonator is excited more than once. Likewise, during the retrace time between  $T_1$  and  $T_2$ , the increase in the frequency of the programmable frequency source 201 is controlled so that no mode of the open resonator is excited more than once. Figures 5A and 5B illustrate non-monotonically changing curves which are analyzed differently than the monotonically changing curves. Figure 5A illustrates that it is improper to count the same mode more than once. Likewise, Figure 5B shows it is improper to count a mode during the increase of the frequency of the programmable frequency source 201 that was not counted during the decrease of the swept frequency.

A first technique to assure that no mode is counted more than once while the frequency of the programmable frequency source 201 is decreasing or more than once while the frequency of the programmable frequency source 201 is increasing depends on the relationship between the slope of the open resonator mode frequency characteristics,  $df_{om}/dt$ , and the slope of the frequency characteristic,  $df_{pfs}/dt$ , where  $t$  is the time, of the programmable frequency source 201. Fig. 2 illustrates the significance of the times to which references are made below.

$T_0 < t < T_1$ . The slope of the PFS frequency characteristic,  $df_{pfs}/dt$ , is to be more negative than the most negative value of the slope of any open resonator mode frequency characteristic,  $df_{om}/dt$ , which it intersects.

$T_1 < t < T_2$ . The slope of the PFS frequency characteristic,  $df_{pfs}/dt$ , is to be more positive than the most positive value of the slope of any

open resonator mode frequency characteristic,  $df_{om}/dt$ , which it intersects.

As indicated in Fig. 2, it is presumed that the steady-state condition has been attained by the time  $T_1$ .

It is well known that the index of refraction  $n$  and the plasma electron density  $N$  may be related to one another by the following approximate formula:

$$n = \sqrt{1 - \frac{Ne^2}{\epsilon_0 m (2\pi f)^2}} = \sqrt{1 - \left(\frac{f_p}{f}\right)^2},$$

where  $e$  is the magnitude of the charge of an electron,  $m$  is the mass of an electron,  $\epsilon_0$  is the permittivity of free space, and  $f_p$  is the plasma frequency. If the equation:

$$\left(\frac{f_p}{f}\right)^2 \ll 1$$

also is true, which it is in the example, it follows that:

$$n \approx 1 - \frac{e^2}{8\pi^2 \epsilon_0 m f^2} N$$

and

$$N \approx \frac{8\pi^2 \epsilon_0 m f^2}{e^2} (1 - n).$$

As discussed above, if the index of refraction is not uniform as a function of position,  $n$  may be replaced by  $\langle n \rangle$ , its mean value along an appropriate path between the reflectors, and  $N$  becomes  $\langle N \rangle$ , its corresponding mean value.

Returning now to the description of Figure 3, Figure 3 shows the computer of Figure 1 as part of the overall plasma processing system. The frequency of the programmable frequency source 201 is controlled by the computer 100 by varying a digital output signal applied to the programmable frequency source 201. (In an alternate embodiment of the present invention, the programmable frequency source 201 receives an analog input, in which case the computer 100 includes or is connected to a digital-to-analog convertor for providing the analog signal to the programmable frequency source 201.) The PFS 201 is connected to an isolator 210a which isolates the programmable frequency source 201 from the plasma chamber 300. The isolator 210a couples an output signal through an iris 310b of an open resonator 305 contained within the plasma chamber 300. The signal reflected back through the iris 310a is coupled to a peak detector 260.

During operation of one embodiment, the computer 100 samples time-dependent inputs from the plasma chamber 300, the plasma generator 320, and a counter 250. (In an alternate embodiment, the counter 250 is moved internal to the computer 100 and the computer uses the output of the peak detector 260 to detect peaks directly – e.g., using interrupts.) Between time  $T_0$  and time  $T_1$ , each time a resonance frequency of the open resonator 305 is excited, a peak in the reflected microwave signal of the open resonator 305 is detected. This peak increases a count of the counter 250 which counts a number of peaks since the last reset signal. Thus, as the frequency of the PFS 201 decreases, the number of modes excited is counted and stored, either in the counter 250 or in the computer 100. For the graph shown in Figure 2, the count would be eight. After the time  $T_1$ , when the PFS frequency begins to increase, the count of the number of resonances as the frequency of the PFS increases is made. For the graph shown in Figure 2, the count would be four. When the PFS has returned to its maximum frequency,  $f_{\max}$  (e.g., 38.75 GHz in Figure 2), the computer 100 begins a search procedure with the aid of the peak detector 260 to return to the final resonance detected. The computer 100

then locks on to  $f_{\text{final}}$  with the aid of the peak detector 260 and appropriate software. The frequency  $f_{\text{final}}$  is measured and stored.

Having determined the number of detected resonance frequencies detected between  $T_0$  and  $T_1$  and between  $T_1$  and  $T_2$ , the computer 100 calculates the fringe order (e.g., 4.288). In order to calculate the corresponding frequency shift, however, the computer 100 also needs the frequency difference between adjacent modes for the empty open resonator, i.e., the mode spacing.

The mode spacing is obtained in advance during a calibration process that is similar to the procedure by which the fringe order was obtained. Figure 4, which is similar to Figure 2, depicts, for the resonance frequencies in an empty open resonator, the modal characteristics which are horizontal and spaced 500 MHz apart for the example considered herein. At the time  $T_0$ , the frequency of the PFS 201 is decreased and then, at the time  $T_1$ , the frequency begins to return to its steady-state value. In this case, however, the computer 100 (1) counts the number of modes excited as the frequency decreases, (2) locks on to the first mode detected, and (3) records the locked frequency. After the frequency has started to increase, the computer 100 searches for and locks on to the final resonance frequency detected with the aid of the peak detector 260 and appropriate software. The computer 100 also measures and stores the final resonance frequency detected.

Based on the data collected during the calibration process and the data sampled during operation, the computer 100 calculates the mode spacings for the empty open resonator 305 and the frequency associated with each resonance for frequencies of interest here.

A more detailed description of the sequence of operations of the apparatus is described below.

- (1) As an optional preliminary step, an equipment operator may elect to monitor that the programmable frequency source is operating within specifications. However, if the operator is confident that the system is operating correctly, this step can be omitted.
- (2) The equipment operator then selects the operating parameters under which the plasma chamber 300 is to operate. The parameters and the

sequence of operation are selected via a data input device (e.g., keyboard 122, mouse 124, or other control panel). The parameters include, but are not limited to, one or more of the following: a desired plasma electron density, a desired index of refraction, the process duration, and the gas to be used.

- (3) After having entered all required data, the operator initiates the process through a data input device.
- (4) The computer 100 controls the calibration of the empty open resonator as described above.
- (5) The computer 100 controls ignition of a plasma in the open resonator 305. As the plasma forms, the computer 100 evaluates (1) inputs (e.g., reflected power) sent to it from the plasma generator 320 and (2) inputs (e.g., optical emissions) sent to it from the plasma chamber 300. The computer 100 controls the frequency of the PFS 201 as described above with reference to Figure 2.
- (6) The computer 100 calculates the fringe order.
- (7) The computer 100 calculates the index of refraction  $n$  or  $\langle n \rangle$ .
- (8) The computer 100 calculates the plasma electron density  $N$  or  $\langle N \rangle$ .
- (9) The computer 100 compares the measured/calculated plasma electron density with the value previously entered by the operator at the operator entry port.
- (10) The computer 100 sends a control signal to the plasma generator 320 to change its output as necessary to maintain the desired plasma electron density.
- (11) The computer 100 repeats steps (6)-(10) throughout the process to keep the plasma electron density at the desired level.

In addition to the above uses, the system must also accommodate an operator's desire to return the system to another state at an arbitrary time. For example, the equipment operator may determine that the electron (plasma) concentration is not optimum for the intended purpose and may want to adjust the concentration. The procedure to be followed will depend on the technique used to track open resonator modes during start-up. The operator enters, by means of a

control console (either local or remote), the value of the desired end parameter (mean index of refraction, electron density, etc., depending on the design of the control console) to be modified.

Although the above description was given assuming a simplified frequency response during plasma initiation, such a response may not occur. A second technique assures that no mode is counted more than once while the frequency of the programmable frequency source 201 is decreasing or more than once while the frequency of the programmable frequency source 201 is increasing. The second technique is similar to the first technique described above but uses a different sweeping technique. The frequency of the programmable frequency source 201 is decreased and increased sequentially a number of times during the time from  $T_0$  to  $T_2$ , as shown in Fig. 6. The sweep can be either periodic or aperiodic. The dependence of the frequency of the programmable frequency source 201 on time is such that the slope of the frequency characteristic satisfies criteria analogous to those enumerated above for the first technique. That is, when the slope of the frequency characteristic,  $df_{PFS}/dt$ , is negative, it is to be more negative than the most negative value of the slope of any open resonator mode frequency characteristic,  $df_{om}/dt$ , which it intersects. Likewise, when the slope of the frequency characteristic,  $df_{PFS}/dt$ , is positive, it is to be more positive than the most positive value of the slope of any open resonator mode frequency characteristic,  $df_{om}/dt$ , which it intersects. These slope conditions are, in general, more easily satisfied in this second technique than in the first, because the time increments during which the frequency of the programmable frequency source 201 decreases or increases are only a small fraction of the time interval between  $T_0$  and  $T_2$ .

In this second technique the modes are counted as in the first technique but for the entire sequence of frequency sweeps. After the steady-state plasma electron density has been attained, the fractional part of the fringe order is determined as described previously for a monotonically increasing plasma electron density.

A third technique employs a frequency-time characteristic of the programmable frequency source 201 such that during start-up no mode is excited in the open resonator in the time interval between  $T_0$  and  $T_2$ , as shown in Fig. 2. Such

a frequency-time characteristic corresponds to no mode shift; i.e., the integer part of the fringe order is zero and need not be considered further. The fractional part of the fringe order can be determined as described previously for a monotonically increasing plasma electron density.

The implementation of this technique requires that the computer 100 be programmed to provide a suitable frequency-time characteristic. An appropriate program can be determined empirically by examining the mode excitations during start-up and changing the program to eliminate them one-by-one, starting with the one first excited after start-up begins.

If the equipment uses the first or second technique to identify mode changes as described above, the PFS sweep is reinitiated and the calibration data and start-up mode data stored in the computer from the immediately preceding start-up are used by the computer to calculate the consequent end parameter change. Such an end parameter may, for example, correspond to an plasma electron density. The computer starts the PFS sweep immediately before it begins to respond to the changed input data. The amount of lead time depends on the various response times of the equipment.

Using the techniques described above, the system can track mode changes generally using a PFS sweep. The system thus determines both the integer and fractional part of any consequent fringe change.

The accuracy of this procedure is limited by the accuracy with which the frequencies involved in the calculations can be measured. The system essentially calculates the index of refraction  $n$  or  $\langle n \rangle$  from the differences of measured frequencies, and these may be difficult to measure with an accuracy better than 0.05%. If this is the case, the index of refraction may be accurate only to about 0.10%, because it is calculated from the ratio of two measured frequencies. Assuming that the index of refraction for a particular case is actually 0.93 (which corresponds to a plasma electron density on the order of  $1 \times 10^{12} \text{ cm}^{-3}$ ), the measured value might be expected to lie between 0.929 and 0.931. The plasma electron density is proportional to  $(1 - n)$  which lies between 0.069 and 0.071 for the

example of Figure 2. Thus, the accuracy with which the plasma electron density may be determined is on the order of  $0.001/0.070 = 1.4\%$ .

As would be evident to one of ordinary skill in the art, the greater the number of modes swept without a plasma, the better the resolution and robustness of the system.

Obviously, numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.